DISCOVERY OF A MAGNETIC WHITE DWARF/PROBABLE BROWN DWARF SHORT-PERIOD BINARY[1]

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ABSTRACT

The magnetic white dwarf SDSS J121209.31+013627.7 exhibits a weak, narrow Hα emission line whose radial velocity and strength are modulated on a period of $\sim$90 minutes. Though indicative of irradiation on a nearby companion, no cool continuum component is evident in the optical spectrum, and IR photometry limits the absolute magnitude of the companion to $M_J > 13.37$. This is equivalent to an isolated L5 dwarf, with $T_{\rm eff} < 1700$ K. Consideration of possible evolutionary histories suggests that, until $\sim$0.6 Gyr ago, the brown dwarf orbited a $\sim$1.5 $M_\odot$ main seqeunce star with $P \sim 1$ yr, $a \sim 1$ AU, thus resembling many of the gaseous superplanets being found in extrasolar planet searches. Common envelope evolution when the massive star left the main sequence reduced the period to only a few hours, and ensuing angular momentum loss has further degraded the orbit. The binary is ripe for additional observations aimed at better studying brown dwarfs and the effects of irradiation on their structure.

Subject headings: stars: low mass, brown dwarfs — stars: individual (SDSS J121209.31+013627.7) — binaries: close — magnetic fields

1. INTRODUCTION

Detached binary systems consisting of a white dwarf plus a nearby low-mass, unevolved companion are of importance because they represent the immediate precursors to cataclysmic variables (CVs) and because their properties allow inferences into the mechanisms and dependencies of common-envelope (CE) evolution. For example, it has been suggested that the lack of magnetic white dwarf + nonmagnetic main-sequence pairs in current catalogs of detached binaries could be due, in part, to the role that a magnetic field on the compact core might play in facilitating the removal of angular momentum (Lemagie et al. 2004; Liebert et al. 2005). The classification process itself is plagued by selection effects, including the larger mean mass (smaller radius) of magnetic *vs.* nonmagnetic white dwarfs (e.g., Liebert et al. 2003), which reduces their detectability against the light of a companion. A strong magnetic field ($B \gtrsim 50$ MG) on a white dwarf also enables the efficient capture of the wind from a low-mass companion, and the resulting weak accretion ($\dot{M} \sim 10^{-13} M_\odot$ yr^{-1}) is detectable as optical/IR cyclotron emission long before the donor's Roche lobe contacts the stellar surface (Schmidt et al. 2005). The binary therefore may escape classification as a detached system, and be included in the Polar class of magnetic CVs[5]. To date, 6 such binaries have been cataloged from spectroscopic searches like the Sloan Digital Sky Survey (SDSS).

In this paper we report the discovery and followup observations of a detached binary with an orbital period of $\sim$90 minutes that contains a magnetic white dwarf and what appears to be a brown dwarf secondary. The lack of ongoing accretion and the relative youth of the white dwarf suggest that the components may have emerged from the CE with an orbital period of only a few hours. The system thus represents an interesting new wrinkle in the tapestry of binary star evolution.

2. OBSERVATIONAL DATA

The star SDSS J121209.31+013627.7 (hereafter SDSS 1212) was reported as a magnetic white dwarf with an equivalent dipolar magnetic field of $B_d = 13$ MG by Schmidt et al. (2003). In the 1 hr SDSS spectrum, obtained on 2002 Jan. 8 and reproduced here as Figure 1, very weak emission appears to be present at Hα[6]. This indicates the presence of a nearby companion that is not apparent as a cool continuum component in the optical spectrum. The emission line was confirmed through spectroscopy at the APO 3.5 m telescope using the DIS spectrograph on 2004 Mar. 28 and 2005 May 14, where the regions $\lambda\lambda 4000 - 5200$ and $\lambda\lambda 5950 - 7600$ were observed in the two spectrograph channels with a resolution of 2Å. Spectropolarimetry was added on 2005 Apr. 14 and 2005 May 16 with the instrument SPOL (Schmidt et al. 1992) at the Bok 2.3 m telescope, covering the region $4200 - 8400$ Å at a resolution of 16Å. Though one of the above runs extends as long as 2.2 hr, no existing data set is ideal for characterizing the behavior of the line emission

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[5] It is strictly a "pre"-Polar.

[6] And possibly at Na I D λ5893, but it is clear from the near-IR portion of this spectrum that sky-subtraction is not excellent.

due to low time resolution, clouds, or strong moonlight.

The Hα emission and Zeeman-split absorption lines are best displayed in the APO results from 2005 May 14 shown in Figure 2. The combined effects of periodic variations in strength and radial velocity that are apparent in the right panel cause the emission line to appear doubled when spectra are coadded over the hour-long sequence. Separations of the principal triplet components of Hα and Hβ indicate a mean surface field of $B_s = 7$ MG. A hint of variation in the shapes of the Zeeman profiles through the series is confirmed by other data sets, and results in smearing across the higher Balmer lines in long exposures.

In an effort to detect the companion star in the infrared, imaging was conducted on 2005 May 20 UT with SpeX, the facility near-IR medium-resolution spectrograph (Rayner et al. 2003) at the 3.0 m NASA Infrared Telescope Facility on Mauna Kea. The spectrograph was configured to an imaging mode using the guiding camera as the detector, which is equipped with a $512{\times}512$ InSb array, to image SDSS 1212 in the Mauna Kea Observatories Near-Infrared J and K bands (Tokunaga et al. 2002). The observations consisted of sequences of dithered 240 s and 120 s exposures for J and K, respectively, using the UKIRT faint standard FS 132 (Hawarden et al. 2001) for photometric calibration. The J-band measurements were obtained in clear conditions and yielded $J = 17.91 \pm 0.05$ for 10 integrations. The K-band results exhibit the systematic effects of rapidly rising humidity that eventually terminated the observations in fog, and will not be reported here.

3. ORBITAL PERIOD

In all data sets of sufficient length, modulations in the equivalent width (EW) and radial velocity of the narrow Hα emission line are apparent. Least-squares sinusoidal fits to the velocities individually yield periods of ∼0.065 d (∼90 minutes), with uncertainties of ∼0.01 d. Unfortunately, at this precision the gaps between observing runs cannot be bridged without cycle-count ambiguities, so the period cannot be refined at this time. However, as a consistency check, all data sets were phased onto a period of 0.065 d and individual phase offsets were applied to register each set to a common curve. The results are plotted in the bottom panel of Figure 3 together with a sinusoid of semiamplitude $K_2 = 320$ (± 20) km s^{-1}. The velocity offset shown, $\gamma = +40$ km s^{-1}, is probably not significant. The shape and amplitude of the variation are reproducible and consistent with the radial velocity curve of a low-mass companion orbiting a white dwarf at a rather high inclination. Indeed, because positive zero-crossing corresponds to inferior conjunction, disappearance of the emission around this phase (see also Fig. 2) supports a high inclination and implies that the line emission is confined to the inner, radiatively-heated hemisphere of the companion. It might be expected that the line strength would then peak near superior conjunction ($\varphi = 0.5$), but the EW values in the top panel are inconclusive on this point. The variation in Zeeman structure on a similar timescale as the emission-line variation that was noted in §2 suggests that the white dwarf spin may be synchronized to the orbital period, as in the Polars. Best estimates for the pertinent parameters of SDSS 1212 are collected together with "psf" magnitudes from the SDSS and our J-band photometry in Table 1.

4. THE STELLAR COMPONENTS

By comparing the survey photometry with colors of non-magnetic DA spectral models (Bergeron et al. 1995) computed in SDSS filter bands, Schmidt et al. (2003) estimated a temperature of $T_{\mathrm{eff}} = 10,000$ K for the white dwarf in SDSS 1212. The Zeeman effect tends to increase the EW of (particularly) Hα and Hβ, thereby depressing g and to a lesser extent r. However, the magnetic field is also known to alter the continuum opacities, at least for fields $B \gtrsim 100$ MG (Merani et al. 1995). Lacking an adequate solution for the entire problem for a magnetic white dwarf photosphere, we adopt the temperature indicated by the nonmagnetic models and quote a liberal uncertainty of $\pm 1,000$ K. The predicted absolute magnitude in SDSS r of 12.27 ± 0.31 ($\log g = 8$, as indicated by the colors) then implies a distance modulus $m - M = +5.80 \pm 0.31$, or $d = 145 \pm 20$ pc, with the error bar dominated by the uncertainty in temperature.

Absolute J-band magnitudes for the same DA white dwarf models range between $12.29 - 11.95$ for $T_{\mathrm{eff}} = 9,000 - 11,000$ K, respectively. Therefore, with a predicted $J_{\mathrm{wd}} = 17.90 \pm 0.14$, the white dwarf alone can account for the total light of the binary ($J = 17.91 \pm 0.05$) at the coolest end of our allowed range. We can set an upper limit for the brightness of the companion by choosing the hottest permissible white dwarf (largest distance modulus; $T_{\mathrm{eff}} = 11,000$ K) and allowing 3σ uncertainties on the photometry, i.e. $J_{\mathrm{min}} = 17.76$. With these assumptions, we find that the companion can contribute at most 21% of the light at 1.25μm, or $J_2 > 19.44$. The implied absolute magnitude is $M_{J,2} > 13.37$. By comparison with the mean characteristics of field L and T dwarfs (Vrba et al. 2004) this corresponds to a spectral type no earlier than L5, $T_{\mathrm{eff}} < 1700$K, and $\log L/L_\odot \leq -4.22$.

Of course, the presence of modulated Hα emission signifies the importance of irradiation by the white dwarf. We cannot directly utilize the line flux to estimate a radiating area, but we point out that the blackbody temperature for reprocessing on the surface of a companion at the implied separation of 0.6 $R_\odot$ is only 1400 K, even assuming an 11,000 K white dwarf, synchronous rotation, and zero albedo. Thus, the consideration of radiative heating cannot yet be used to further constrain the nature of the companion.

The very low inferred luminosity for the companion in SDSS 1212, its large radial velocity amplitude, the presence of hydrogen at its surface, and the length of its orbital period argue that the star is a low-mass object near the cool end of the main sequence, as opposed to, e.g., the eroded core of a double-degenerate (white dwarf + white dwarf) binary. The stellar properties derived from the J-band flux are actually near the terminus of hydrogen-burning stars ($M_2 = 0.07 - 0.09$ $M_\odot$; e.g., Chabrier & Baraffe 2000), but the fact that the J-band luminosity is an upper limit coupled with the high degree of irradiation prompt us to refer to the companion star as a brown dwarf.

5. NATURE OF THE BINARY

We can imagine two possible evolutionary histories for the SDSS 1212 system. The first takes the binary to be an

old Polar in a protracted (>3 yr) state of weak or nonexistent accretion. EF Eri is a well-known example with $P = 81$ minutes and $B = 18$ MG that has been a subject of special interest since it lapsed into a very low state in 1997. Though previously thought to contain an $L4 - 5$ brown-dwarf companion (Howell & Ciardi 2001; Harrison et al. 2003), evidence for IR cyclotron emission by Harrison et al. (2004) calls this into question. The white dwarf temperature is similar to that in SDSS 1212 at $T_{\rm eff} = 9,500$ K.

If we make the standard assumption that pre-CVs emerge from the CE at orbital periods of several hours to days (Taam & Bodenhemier 1989, 1991; but see Livio 1982 for an alternate route), the evolutionary time to $P \sim 90$ minutes is >1 Gyr. For this age, the radius throughout the L and T sequence is similar to that of Jupiter (Burrows et al. 1997), and a factor of 2 smaller than the Roche lobe. Therefore, if SDSS 1212 is a Polar in a low state, the companion must be kept artificially inflated during its accretion episodes by radiative heating. This picture also requires that the white dwarf exhibit the effects of accretion-induced heating, since an isolated $0.6\ M_\odot$ white dwarf cools to $T_{\rm eff} = 10,000$ K in ~ 0.6 Gyr. Moreover, because accretion only affects the envelope, the cooling timescale following a lapse of mass transfer falls in the range weeks to years (Godon & Sion 2002), so it would seem highly improbable to have discovered SDSS 1212 in this curious state.

A second, more likely, scenario assumes that the binary is currently and has always been detached - i.e., that it has never experienced a CV phase. In this case the companion was "born" as a brown dwarf in an initial orbit with $P \sim 1$ yr, $a \sim 1$ AU, i.e., similar to many of the gaseous superplanets being found in current extrasolar planet surveys. The orbital period would have decayed to a few hours during the CE stage, and the binary presumably has evolved since by the usual gravitational radiation and magnetic braking angular momentum loss mechanisms. The post-CE age of the binary is then simply the ~ 0.6 GY cooling time of the white dwarf, and the total age of the brown dwarf is that number added to the few GY lifetime of the main-sequence parent (for $M_{\rm MS} = 1.5\ M_\odot$). This, of course, implies that detached binaries can emerge from the CE at short orbital periods, a fact already indicated by population models (Politano 2004) and by the existence of the 2.7 hr period binary nucleus in the planetary nebula Abell 41 (Grauer & Bond 1983). While this picture involves fewer phases of evolution, it is no less interesting, for it offers the possibility of studying the effects of irradiation on a brown dwarf of known age and history.

6. DIRECTIONS FOR FUTURE STUDY

Clearly, K-band photometry and spectroscopy are essential. Unfortunately, because of its greater distance, detection of the companion in SDSS 1212 may prove to be more difficult than for EF Eri, which has not yet yielded a clear result despite the use of the world's largest telescopes. An improved Hα radial velocity curve is both desirable and feasible. An accurate trigonometric parallax would better constrain the nature of the secondary, but with the white dwarf dominating even at J, accurate model flux distributions of magnetic degenerate stars are required before the companion's spectrum can be extracted with confidence. The amplitude of variation of the IR light curve would allow the effects of irradiation on the brown dwarf to be assessed and compared with models of the type now under development (e.g., Burrows et al. 2004). There is also the possibility of a <5 minute eclipse of the white dwarf, a phenomenon that could potentially yield a radius for the companion. This is amenable to the optical but has not yet been explored through time-series photometry. Finally, because the temperature of the white dwarf in SDSS 1212 is very near the range occupied by the ZZ Ceti stars, an accurate mass for the white dwarf might be available by pulsation analysis. This assumes that the magnetic field does not quench the pulsations (Schmidt & Grauer 1997; Morsink & Rezania 2002). One might even hope to determine the mass ratio $q = M_2/M_1$ and thus the brown dwarf mass itself by measuring the time delay in pulsation peaks across the white dwarf's orbit.

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TABLE 1

PROPERTIES OF
SDSS J121209.31+013627.7

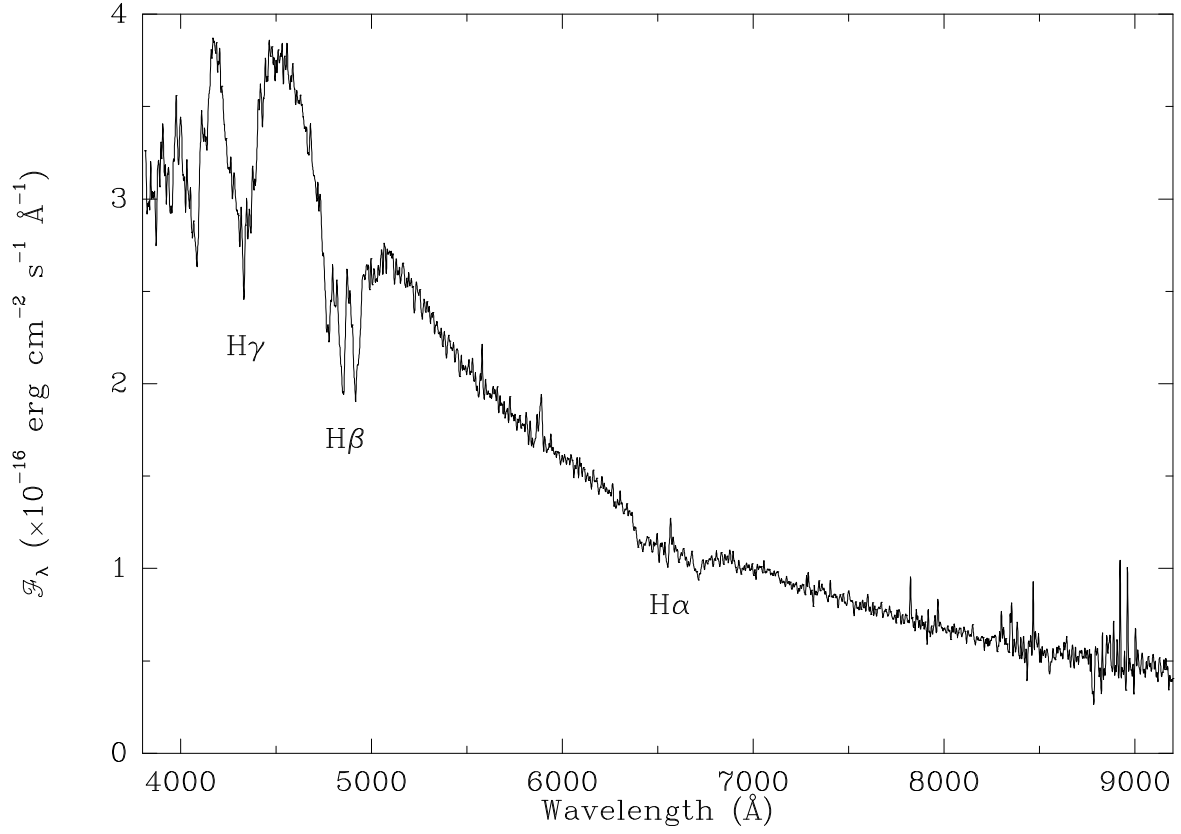|	
u	18.43 ± 0.03
g	17.99 ± 0.02
r	18.07 ± 0.02
i	18.24 ± 0.02
z	18.40 ± 0.03
J	17.91 ± 0.05
T_{wd}	$10,000 \pm 1,000$ K
B_d	13 MG
P	0.065 ± 0.010 d
K_2	320 ± 20 km s^{-1}

F‍IG. 1.— Survey spectrum of SDSS J121209.31+013627.7 showing Zeeman splitting in a mean surface field of 7 MG ($B_d = 13$ MG). Note the weak emission at Hα but lack of evidence for the continuum of a late-type companion in the red. Difficulties with sky subtraction are evident beyond 7500Å and may contribute to the appearance of Na I D weakly in emission.
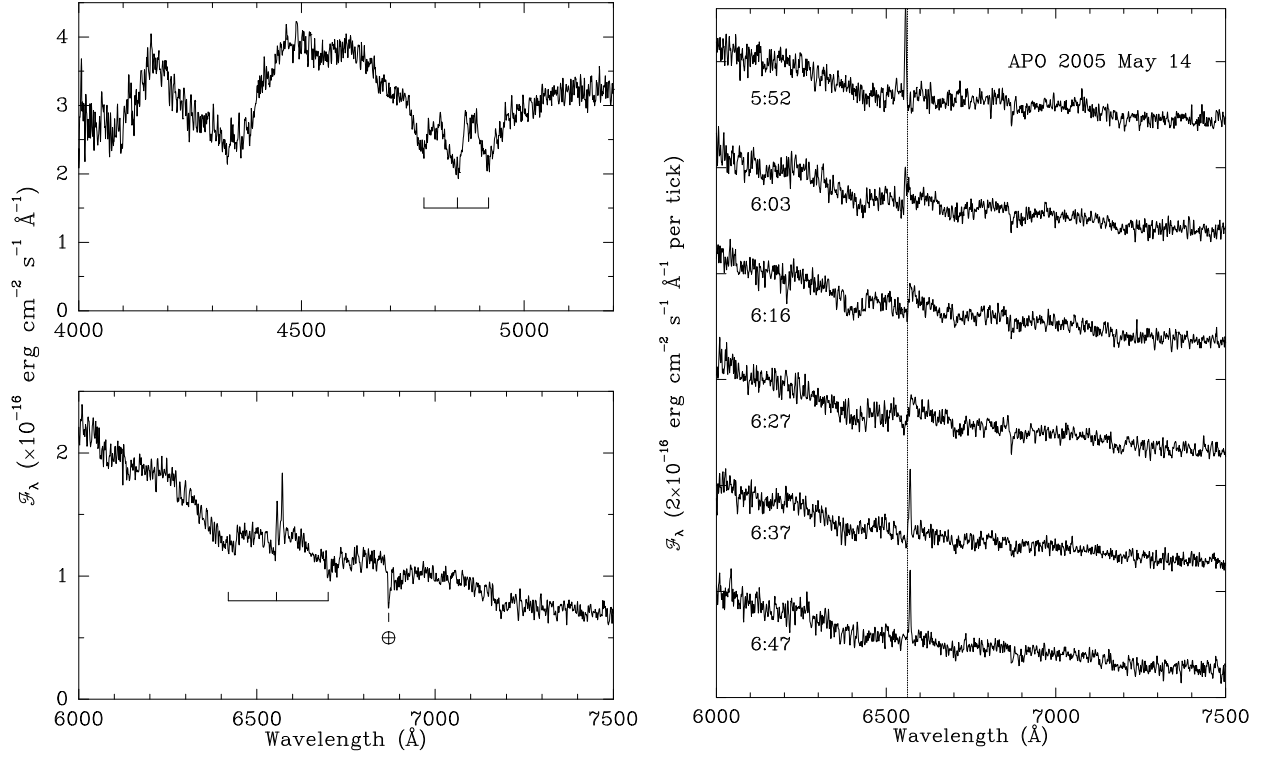
FIG. 2.— *(Right):* One-hour spectroscopic sequence around Hα on 2005 May 14, with the mid-UT of each exposure indicated. Successive spectra are displaced by 2×10^{-16} erg cm^{-2} s^{-1} Å^{-1} and a dotted line at the rest wavelength of Hα reveals the emission-line velocity shift over the series. *(Left):* The coadded blue and red spectroscopic channels from the same data set showing the Zeeman absorption triplets at Hα and Hβ, and a doubled appearance of the Hα emission line that arises from the combined radial velocity and flux modulation of the line.
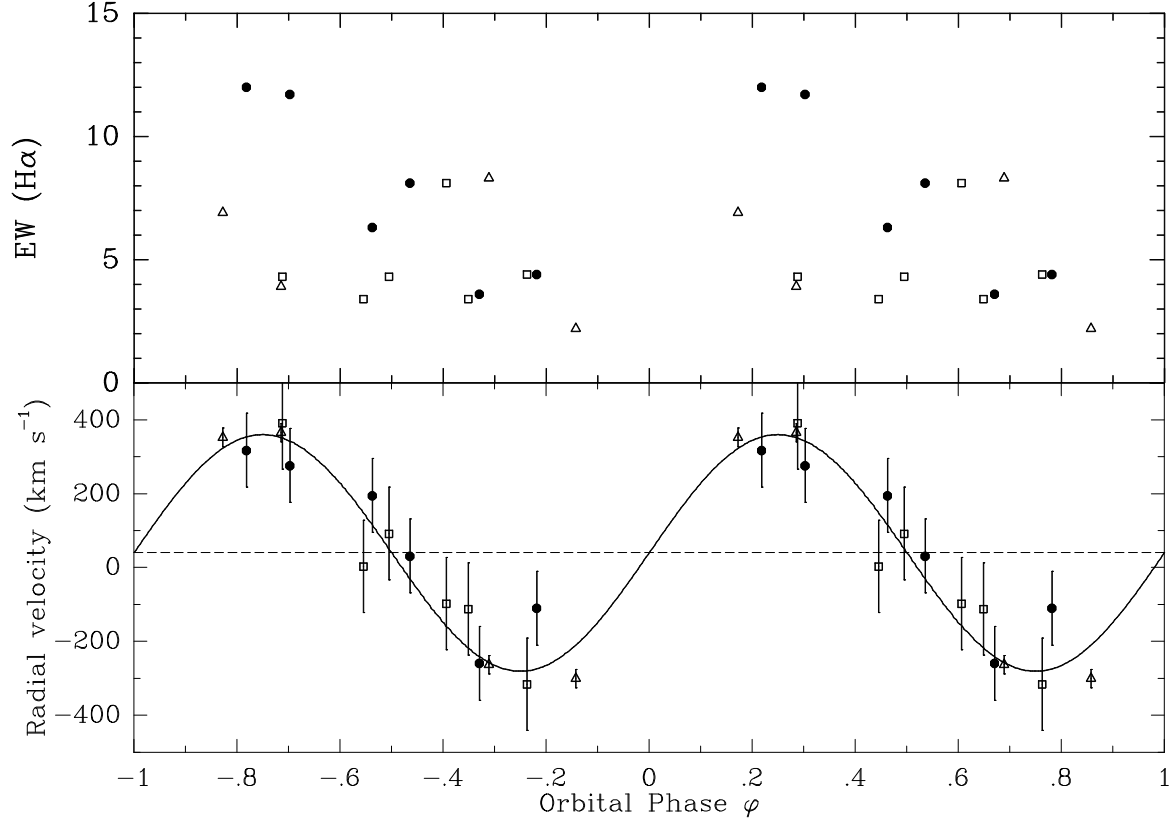
Fig. 3.— Radial velocity *(bottom)* and equivalent width (EW) *(top)* of Hα for all spectroscopic runs, with individual phase offsets applied to register the velocity curves to the mean behavior. The orbital period is $P = 0.065 \pm 0.01$ d and radial velocity semiamplitude $K_2 = 320 \pm 20$ km s^{-1}. Disappearance of the line around inferior conjunction ($\varphi = 0$) indicates that line emission is confined to the inner, radiatively-heated hemisphere of the companion, and that the system is viewed from a high inclination. Symbol key: *(filled circles:)* 2004 Mar. 28; *(triangles):* 2005 May 14; *(squares):* 2005 May 16. The data are plotted twice for clarity.